

Structural Analysis of Lightning Protection System for New Launch Vehicle



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Introduction: This project includes the design and specification of a lightning protection system for Launch Complex 39 B (LC39B) at Kennedy Space Center, FL in support of the Constellation Program. The purpose of the lightning protection system is to protect the Crew Launch Vehicle (CLV) or Cargo Launch Vehicle (CaLV) and associated launch equipment from direct lightning strikes during launch processing and other activities prior to flight. The design includes a three-tower, overhead catenary wire system to protect the vehicle and equipment on LC39B as described in the study that preceded this design effort: KSC-DX-8234 "Study: Construct Lightning Protection System LC39B".

The study was a collaborative effort between Reynolds, Smith, and Hills (RS&H) and ASRC Aerospace (ASRC), where ASRC was responsible for the theoretical design and risk analysis of the lightning protection system and RS&H was responsible for the development of the civil and structural components; the mechanical systems; the electrical and grounding systems; and the siting of the lightning protection system. The study determined that a triangular network of overhead catenary cables and down conductors supported by three triangular free-standing towers approximately 594 ft tall (each equipped with a man lift, ladder, electrical systems, and communications systems) would provide a level of lightning protection for the Constellation Program CLV and CaLV on Launch Pad 39B that exceeds the design requirements.

Structural Analysis Methodology: The design of the lightning protection towers was an iterative process including several structural analysis computer models. A preliminary tower model based on the dead, live, and wind loads was modeled using stiffness model analysis software. The stiffness of the tower model was obtained such that simplified versions of each tower could be and incorporated into a larger GT STRUDL model consisting of three towers and the lightning protection cable array. Dead loads and wind loads acting on the cables in the GT STRUDL model provided updated information for the stiffness model analysis software modeling of the towers. As a result of the unique angles that the cable array makes with each of the three towers, individual stiffness models are used for each of the lightning protection towers. Steel member selection changes are made such that all three towers will be identically constructed with the exception of the cable array connection ring at the top of the lightning mast. The member selection process provides updated stiffness of the towers, resulting in a change to the GT STRUDL cable array model, and thus continuing the cycle of design. This iterative procedure was continued until the design of the towers and the cable array converged into a code satisfactory and constructible solution.

The design of the lightning masts that top each of the lightning protection towers will be finalized by the fiberglass reinforced polymer (FRP) manufacturer/fabricator. A performance specification for the design of these structures was developed from a preliminary structural analysis to provide minimum required structural properties for use in the design of the resin and reinforcing matrix that will make up the composite structures.

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GT STRUDL User's Group Presentation
Las Vegas, NV June 23-26, 2008

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Agenda

- System Description and Requirements
- Conceptual Development
- Structural Analysis Methodology
- Resulting Structural System
- Construction Considerations
- Construction Status

Lightning Protection System

Artist's rendering:



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System Description & Requirements

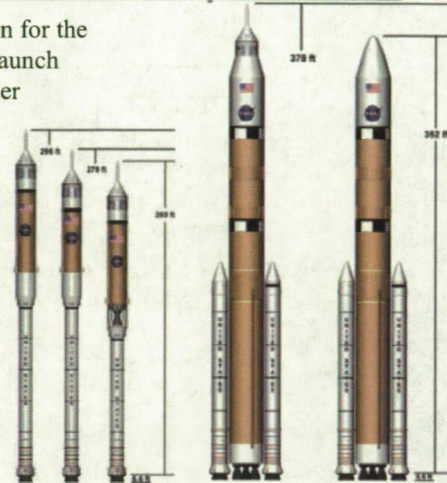
- 594' Self Supporting Towers
 - Site conditions prevented Guyed Towers
- 90' Fiberglass Lightning Mast
 - 7' Diameter
- Stainless Steel Cable Array System
 - Overhead Wires
 - Down Conductor Wires

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System Description & Requirements

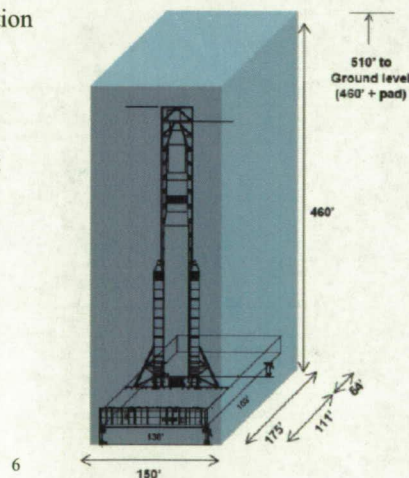
- Purpose: Provide lightning protection for the Constellation Program vehicles at Launch Complex 39B, Kennedy Space Center
 - Concept Crew Launch Vehicle
 - Concept Cargo Launch Vehicle

- Note: Vehicles are currently under development. Sketches to the right are artists' renderings of possible vehicles.



System Description & Requirements

- Largest possible launch configuration requiring protection defined by volume shown to the right
- Minimum clearance from the protected envelope to overhead lightning conductor system = 40 ft
- Flashover distance from support towers to overhead lightning conductor system = approx. 50 ft
- System must provide adequate clearance for roll out and launch, including drift cone
- Steel design per AISC 9th Edition ASD

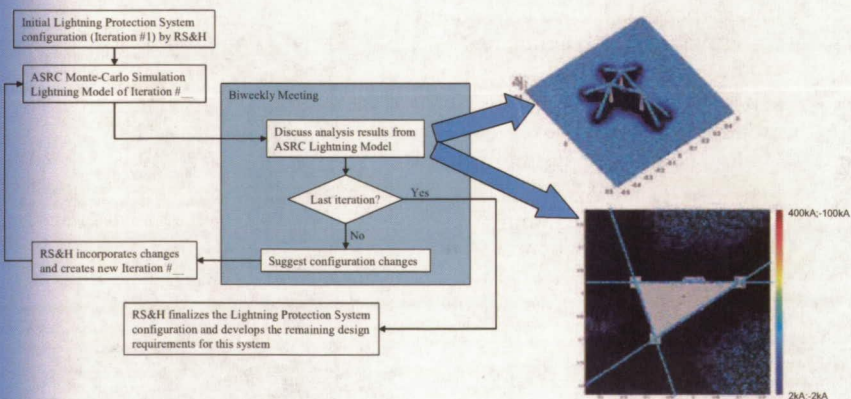


Conceptual Development

- Study Phase
 - Iterative process:
 - RS&H provided structural and mechanical layout for concepts
 - ASRC provided Monte Carlo based lightning strike analysis to determine risk
 - NASA determined if risk exceeded, met, or failed to meet program goals
 - Result of study = concept for design
- Design Phase
 - RS&H provided a design based on the concept derived during the study phase

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Conceptual Development Study Phase

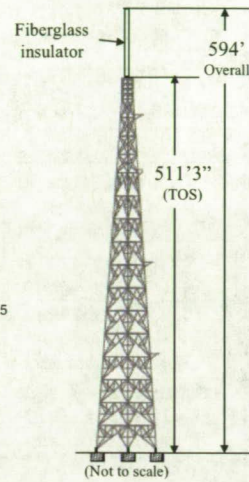
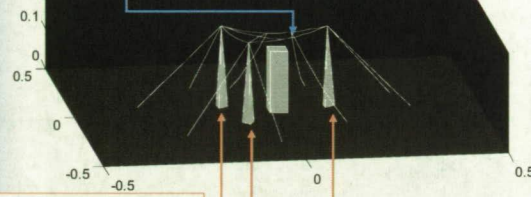


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Resulting Concept for Design

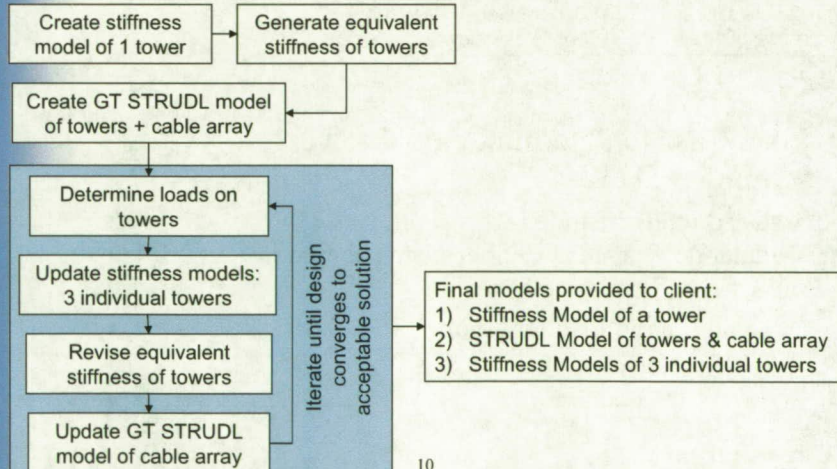
Overhead SST wire rope array

3 Triangular Towers



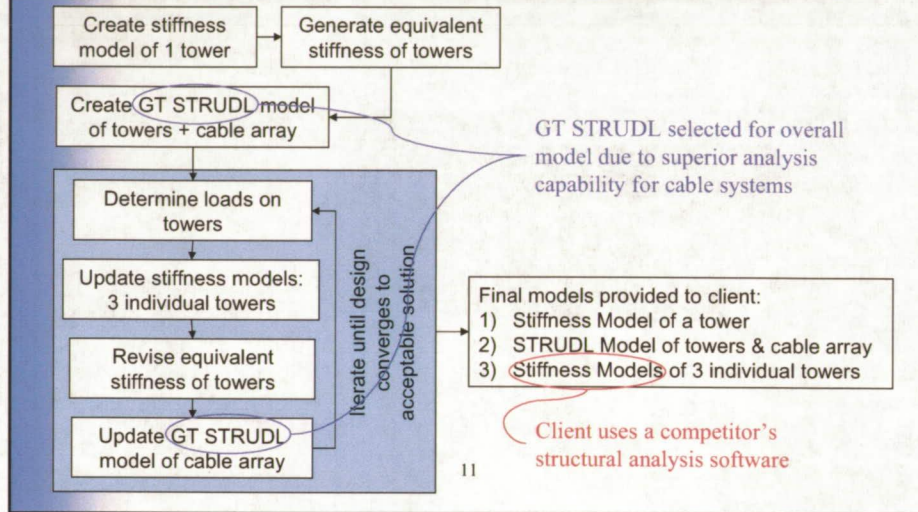
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Structural Analysis Methodology

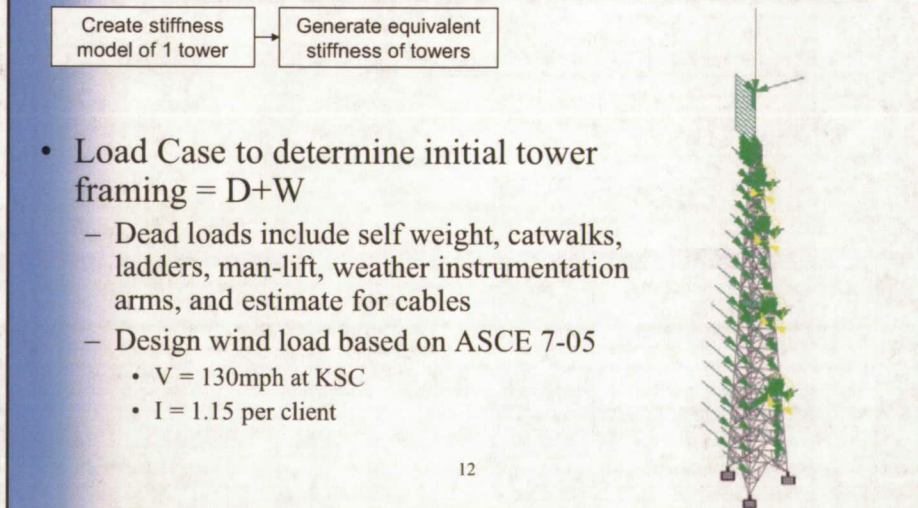


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Structural Analysis Methodology



Structural Analysis Methodology

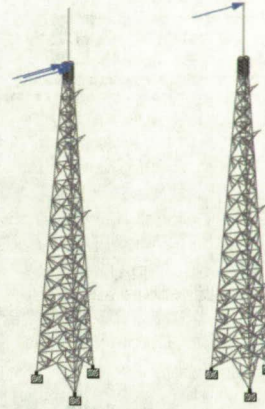


Structural Analysis Methodology

Create stiffness
model of 1 tower

Generate equivalent
stiffness of towers

- Initial stiffness determined by
point loads vs. deflection
 - Stiffness for steel portion
 - Stiffness for fiberglass mast



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Structural Analysis Methodology

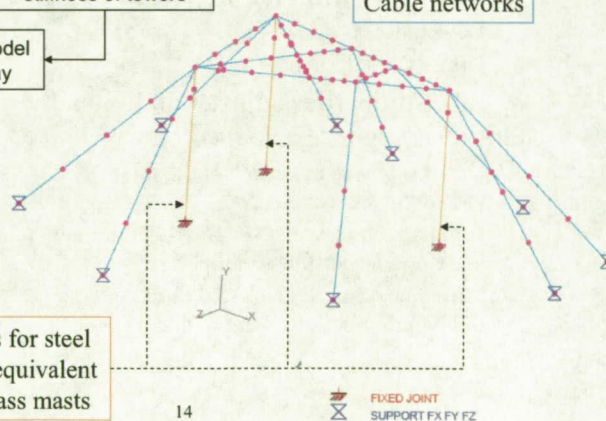
Create stiffness
model of 1 tower

Generate equivalent
stiffness of towers

Create GT STRUDL model
of towers + cable array

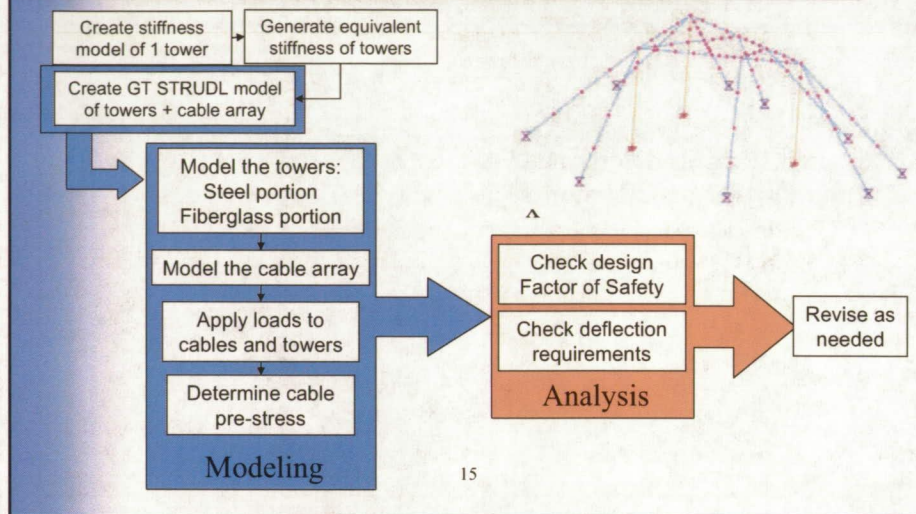
Cable networks

Equivalent beams for steel
tower, topped by equivalent
beams for fiberglass masts



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GT STRUDL Modeling

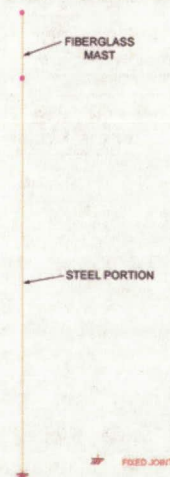


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Model Towers → Model cables → Apply loads → Determine pre-stress

GT STRUDL Tower Models

- The tower was separated into 2 segments with different member properties
 - Lower steel portion
 - Upper fiberglass mast
- Member properties adjusted individually until convergence achieved
 - Deflection was measured at the top of steel and top of fiberglass
 - Comparison between GT STRUDL model and previous stiffness model
 - Moments of inertia adjusted until deflections in 8 wind directions were within 5%



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GT STRUDL Tower Models

- The Tower Models were input based on section properties instead of a specific member size.

— Fiberglass Mast

UNITS FEET LBS DEG FAH

MEMBER PROPERTIES AX 3.6 IY 5.85 IX 5.85 IZ 5.85

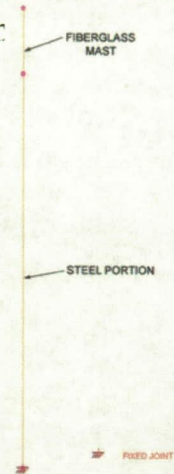
120

— Steel Portion

UNITS FEET LBS DEG FAH

MEMBER PROPERTIES AX 2.83 IY 750 IX 750 IZ 750

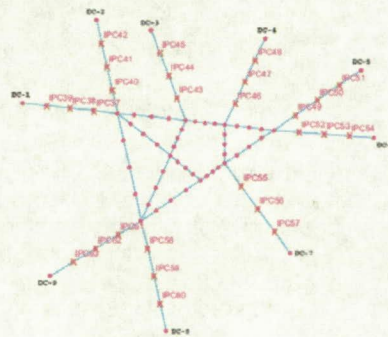
121



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GT STRUDL Cable Network

- After towers modeled, the cable network was created in GT STRUDL
- Cable layout was drawn in AutoCAD
 - End Point Nodes input into GT STRUDL
 - Elements drawn between the nodes to produce the Cable Analysis Model



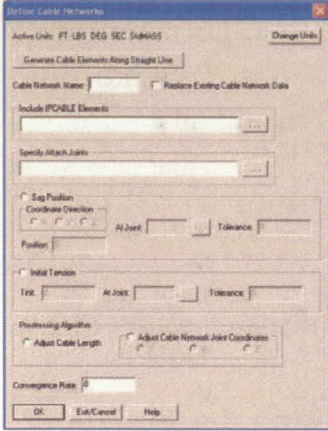
18

Model Towers
Model cables
Apply loads
Determine pre-stress



GT STRUDL Cable Network

- Each element that was connected to main connection points was divided using the “Define Cable Networks” command.
- This command was used to generate each segment of the cable network.



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Model Towers
Model cables
Apply loads
Determine pre-stress



GT STRUDL Cable Network

- Each main cable element between connection points was divided into 4 segments
- Connection points = down conductor anchors, towers, or connection plates
- A total of 21 groups were created using this methodology.

```

DEFINE CABLE NETWORK 1
  INCLUDE ELEMENTS EXISTING 'IPC1' TO 'IPC4'
  ATTACH JOINTS EXISTING 'T1-T' 5
  INITIAL TENSION TO 11000.0 TOLERANCE 1100.00 JOINT 'T1-T'
  ADJUST LENGTH
  CONVERGENCE RATE 1.00000
END
DEFINE GROUP 1 ADD ELEMENTS EXISTING 'IPC1' TO 'IPC4'
  
```

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Model Towers

Model cables

Apply loads

Determine pre-stress



GT STRUDL Cable Network

- Initial Cable Sizes
 - Down Conductors from Towers were 3/4"
 - Down Conductors from other cables were 3/4"
 - Primary Catenary Cables were 1-1/4"
 - Secondary Catenary Cables were 3/4"
- Primary Catenary Cable Size Command

```

UNITS FEET LBS DEG FAH
ELEMENT PROPERTIES TYPE 'IPCABLE' AX 0.0049 SW 2.9 DIR -Y LF 0.990000
      'IPC1'  'IPC2'  'IPC3'  'IPC4'  'IPC5'  -
            
```

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Model Towers

Model cables

Apply loads

Determine pre-stress



GT STRUDL Model Loads

- Wind loads on cables
 - Determined using ASCE 7-05
 - Applied along cables using GT STRUDL “Edge Force” load type.
- Example of North Wind on one section of Primary Catenary Cables:

```

UNITS FEET LBS DEG FAH
CHANGES
LOAD 2
ADDITIONS
ELEMENT LOADS
      'IPC1' TO 'IPC12' EDGE FORCE GLOBAL UNIFORM LZ 7.5
            
```

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Model Towers

Model cables

Apply loads

Determine pre-stress



GT STRUDL Model Loads

- Wind loads applied to the tower models

MEMB LOADS FOR Z GLO LIN FRA WA 820 WB 820 -

LA 0.0000000E+00 LB 0.0378

111 121 131
- Connection plate loads were estimated and applied at intersection points

LOADING 'I' 'Prestress - DEAD LOAD'

JOINTS EXISTING 4 LOAD FORCE Y -32

JOINTS EXISTING 5 8 15 LOAD FORCE Y -110

JOINTS EXISTING 16 LOAD FORCE Y -90

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Model Towers

Model cables

Apply loads

Determine pre-stress



Cable Pre-Stress

- Iterative task of prestressing the cables:
 - Initial pre-stress values were over 50% of the breaking strength
 - Several attempts produced non-converging networks

**** INFO_CBNTAN -- CABLE PRESTRESS ANALYSIS

HAS NOT CONVERGED AFTER 100 ITERATIONS.

CHECK CABLE PRESTRESS ANALYSIS CONTROL PARAMETER.
 - Help from GT STRUDL (Mike Swanger) obtained

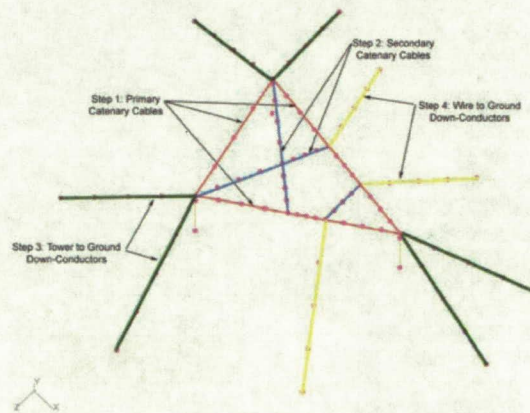
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Cable Pre-Stress

- Problem = network size
 - Analysis of entire network could not converge regardless of the initial stress values
- Solution = stepped analysis procedure
 1. The primary catenary cables
 2. The secondary catenary cables
 3. The tower down-conductors
 4. The wire to ground down-conductors

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Cable Pre-Stress



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Model Towers

Model cables

Apply loads

Determine pre-stress



Cable Pre-Stress

- By using a stepped analysis procedure the cable network was able to solve.

**** INFO_STN3BS -- Nonlinear analysis for loading condition 1 has converged after 121 iterations. Nonlinear analysis for this loading condition will be suspended.

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Create stiffness model of 1 tower

Generate equivalent stiffness of towers



GT STRUDL Modeling

Create GT STRUDL model of towers + cable array

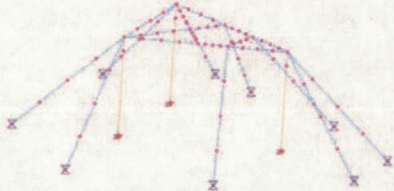
Model the towers:
Steel portion
Fiberglass portion

Model the cable array

Apply loads to cables and towers

Determine cable pre-stress

Modeling



Check design Factor of Safety

Check deflection requirements

Analysis

Revise as needed

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GT STRUDL Analysis

- Analysis of Design Factors of Safety
 - Design Factor of Safety = actual cable stresses vs. breaking strength
 - Limit selected of 1.5 for hurricane load conditions
- Analysis of cable deflections
 - Clear distance ≥ 40 feet above vehicle envelope at vehicle entryway
 - Goal of minimizing deflections at the top of the towers under dead load condition

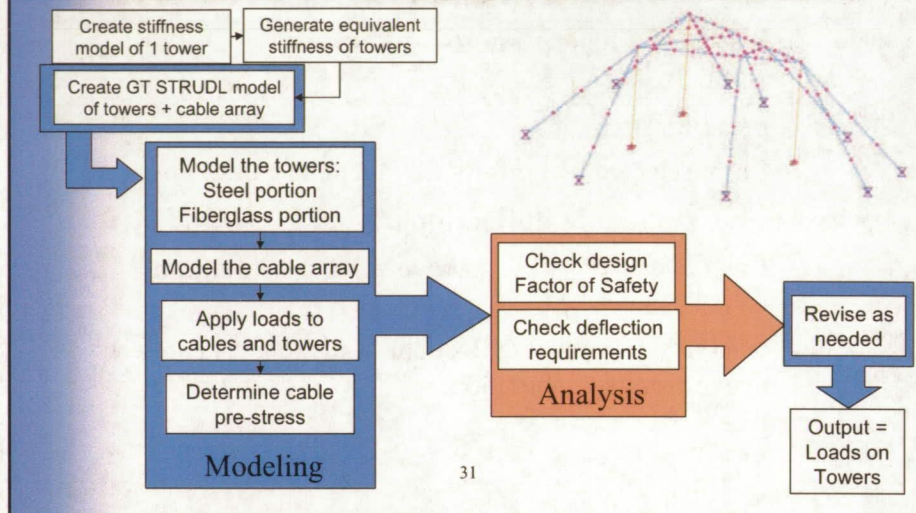
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GT STRUDL Analysis

- The initial run did not pass the cable stress or displacement requirements
- Iterative solution process:
 - Cable sizes revised
 - Pre-stress values adjusted for new breaking strengths
 - Re-analysis of factor of safety and deflection
- This process was repeated several times until the design was adequate

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GT STRUDL Modeling



GT STRUDL Output

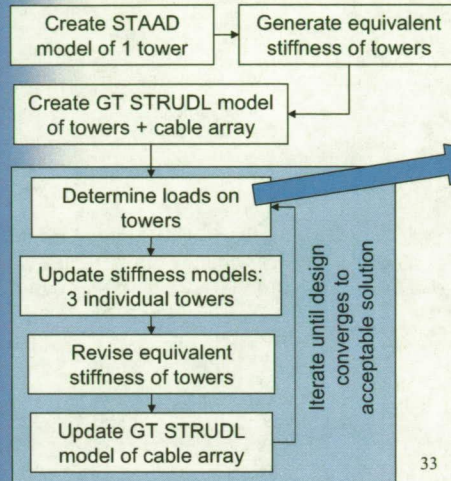
- Example of Cable Stress Results using "LIST STRESSES ELEMENTS EXISTING GROUP LIST 1 ELEMENTS" Command

LOADING - 1 Prestress - DEAD LOAD

ELEMENT STRESSES
ELEMENT

IPC1	NODE T1-T	Sxx	3366105.	Force	10434.93
	NODE IPC1	Sxx	3354110.	Force	10397.74

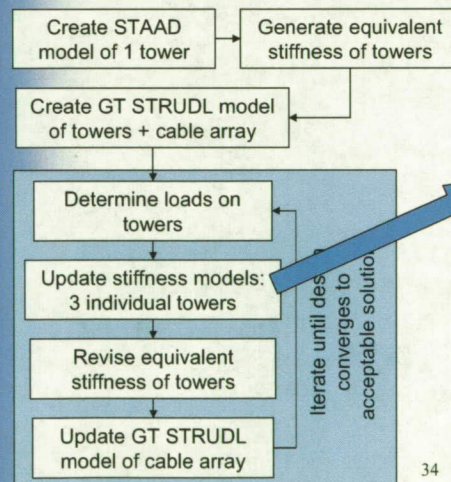
Structural Analysis Methodology



- GT STRUDL output provides loads from cable network to towers at top of tower node for each load case:
 - Dead loads
 - Dead + wind (east)
 - Dead + wind (west)
 - Dead + wind (north)
 - Dead + wind (south)
 - Dead + wind (northeast)
 - Dead + wind (northwest)
 - Dead + wind (southeast)
 - Dead + wind (southwest)

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Structural Analysis Methodology

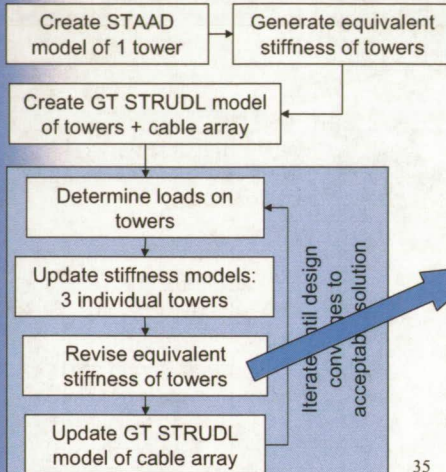


- Cable loads updated on individual models* of each tower
- Towers evaluated for code compliance
- Steel framing updated as required*

* Towers designed to be identical (same framing), though the cable array attachment is unique to each tower.

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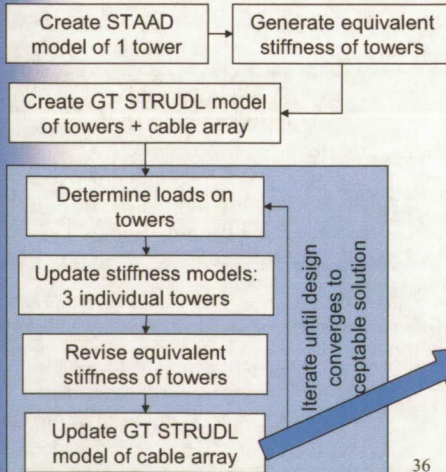
Structural Analysis Methodology



- Initial stiffness updated to reflect changes in structural geometry and member sizing

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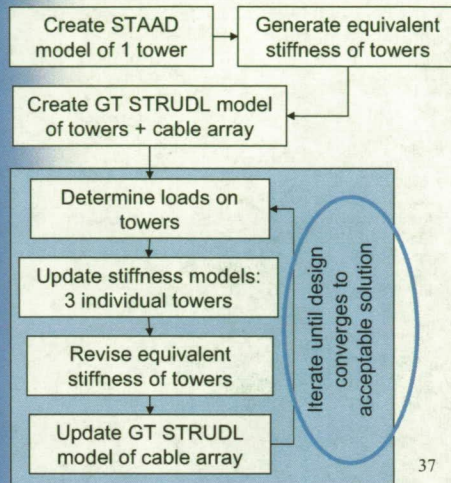
Structural Analysis Methodology



- Update stiffness values
- Re-analyze cable array
- Revise cable pre-stress as required

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Structural Analysis Methodology



- Repeat the steps with the new cable array loads
- Iterate until no new changes required in the tower structural framing

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Final GT STRUDL Model

- After developing the STRUDL model significant changes in the original cable sizes were made:

Cable	Initial Cable Sizes	Final Cable Sizes
Primary Catenary	1-1/4 in	1 in
Secondary Catenary	3/4 in	5/8 in
Wire to Ground Down-Conductors	3/4 in	5/8 in
Tower to Ground Down-Conductors	3/4 in	1-1/4 in

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Final GT STRUDL Model

- The reactions at the down conductor pile caps were utilized to select the appropriate uplift loads for the foundation design

--- LOADING - 1 Prestress - DEAD LOAD

RESULTANT JOINT LOADS SUPPORTS

JOINT		FORCE			MOMENT		
		X FORCE	Y FORCE	Z FORCE	X MOMENT	Y MOMENT	Z MOMENT
DC-1	GLOBAL	-11138.23	-11185.04	-1178.20			
DC-2	GLOBAL	-2781.83	-12649.74	-12412.33			
DC-3	GLOBAL	-484.42	-1081.20	-1374.31			
DC-4	GLOBAL	563.86	-1040.95	-1264.42			
DC-5	GLOBAL	7741.53	-8016.00	-5326.69			
DC-6	GLOBAL	12148.81	-11380.39	887.65			
DC-7	GLOBAL	965.36	-1062.96	1345.87			
DC-8	GLOBAL	2961.01	-11304.67	13213.23			
DC-9	GLOBAL	-10016.75	-10275.89	6059.99			

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Final GT STRUDL Model

- Effects of thermal loads were checked under two different temperature deltas, -40°F and $+50^{\circ}\text{F}$, which equates to a real world temperature range of 30° to 120° Fahrenheit. These values were used to better define cable erection procedures during construction.

\$*****DELTA OF -40 DEG*****

UNITS FEET LBS DEG FAH
CHANGES

LOAD 10
ADDITIONS

JOINT 'IPC1' TO 'IPC63' TEMPERATURE CHANGE -40.0
JOINT 4 5 8 15 16 TEMPERATURE CHANGE -40.0

CONVERGENCE TOLERANCE EQUILIBRIUM 0.01
MAXIMUM NUMBER OF CYCLES 100

LOAD LIST 10
NONLINEAR ANALYSIS

\$*****DELTA OF 50 DEG*****

UNITS FEET LBS DEG FAH
CHANGES

LOAD 11
ADDITIONS

JOINT 'IPC1' TO 'IPC63' TEMPERATURE CHANGE 50.0
JOINT 4 5 8 15 16 TEMPERATURE CHANGE 50.0

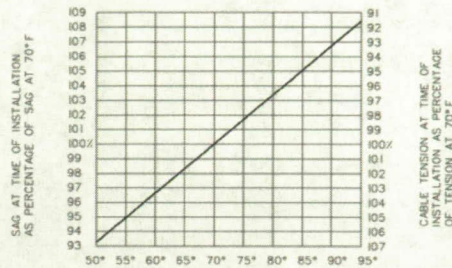
CONVERGENCE TOLERANCE EQUILIBRIUM 0.01
MAXIMUM NUMBER OF CYCLES 100

LOAD LIST 11
NONLINEAR ANALYSIS

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Final GT STRUDL Model

- The results of the thermal analysis were used to generate a cable sag and tension adjustment diagram.



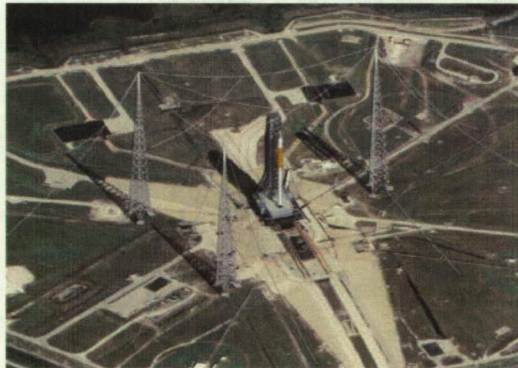
NOTE:
TENSION AND SAG SHOWN CORRESPOND TO AMBIENT TEMP. OF 70°F. IF THE AMBIENT TEMPERATURE AT THE TIME OF CABLE INSTALLATION IS DIFFERENT THAN 70°F, ADJUST THE TENSION AND SAG IN ACCORDANCE WITH THE ABOVE CHART.

CABLE SAG AND TENSION TEMP. ADJ.-DETAIL

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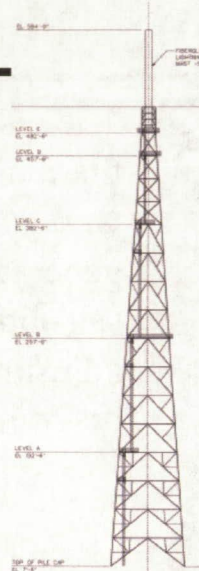
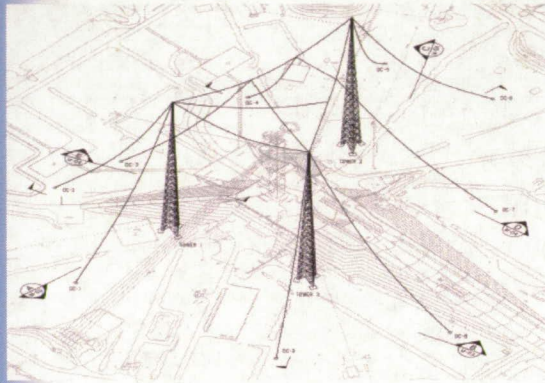
Resulting Structural System

Artist's rendering:



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Resulting Structural System



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Status of Construction

Pile driving 11/07 – 02/08



Tower foundations:
20 Piles per leg
50-55 ft deep

Temporary road base
constructed as a work
area for large crane

Temporary road base
for access / smaller
cranes

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Status of Construction



Rebar & anchor bolt placement
12/07 – 03/08

Anchor bolts:
20 per leg
2 ½ in diameter
5ft 4in long
(approx 90 lbs each)

45

Status of Construction



Rebar & anchor bolt placement
12/07 – 03/08

Steel frame to keep
anchor bolts in place
during concrete
placement

#11 bars each way
top & bottom,
wrapped at sides

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Status of Construction

Rebar & anchor bolt placement
12/07 – 03/08



Steel frame to keep
anchor bolts in place
during concrete
placement

#11 bars each way
top & bottom,
wrapped at sides

Additional bars at
anchor bolts for shear
(difficult to photo)

#5 bars along vertical
edges

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Status of Construction

Concrete placement – Tower #2 02/08, Tower #1 03/08



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Status of Construction

Concrete placement – Tower #3 03/27



Pad 39B Fixed Service Structure (FSS) and Rotating Service Structure (RSS) in the background

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Status of Construction

Steel arrives June 2008

Expected completion
Spring 2010



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Structural Analysis of Lightning Protection System for New Launch Vehicle

Questions?



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